ORAL/POSTER REFERENCE:ICF100769OR

VALIDITY REQUIREMENT FOR THE CNT SMALL SPECIMEN TESTING PROCEDURE TO EVALUATE FRACTURE TOUGHNESS

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ABSTRACT

This paper presents the cylindrical notched test (CNT) specimen for evaluation of K_{Ic}. The specimen geometry is the smallest which can produce values of K_{Ic} which are very nearly valid in respect to such testing and much smaller than the standard compact tension test (CTT) specimen.

INTRODUCTION

The determination of fracture toughness (characterised by the material property K_{Ic}) is of considerable importance for materials used in mechanical engineering. Fracture toughness is the measure of the material's resistance to crack growth. At present K_{Ic} is determined using standard compact tension test (CTT) specimens which are expensive to manufacture and require relatively sophisticated laboratory equipment.

Because of the inconvenience of the CTT specimen there has been a quest for smaller specimens and a wide variety of smaller tests have been used. Many of the tests such as Charpy, Izod and punch tests can only be described as comparative tests since the geometry of the final crack cannot give valid values of $K_{Ic.}$

An extensive research program which began in 1985, and is still continuing[123], has indicated the effectiveness of a new small specimen for determining valid fracture toughness values. The cylindrical notched test (CNT) K_{Ic} Fracture Toughness Specimen[4] is now being evaluated as a standard test specimen by the American Society for Testing Materials (ASTM) and could make a major impact on material testing practices. The CNT specimen is shown in Figure 1 and compared to a CTT specimen in Figure 2

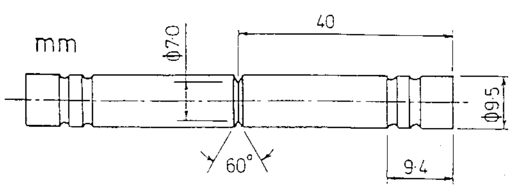

Figure 1. Cylindrical notched test (CNT) specimen. All dimensions in mm.

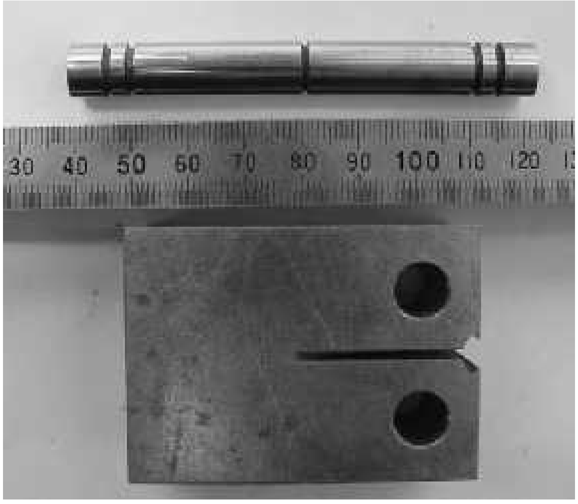

Figure 2 A valid ASTM CTT specimen (bottom) compared to cylindrical CNT specimen for the same material.

Procedure of CNT tests
The test procedure involves machining the specimen from the material to be tested including a circumferential vee notch as shown on Figure 1. A crack is then grown from the base of the notch in a rotating fatigue machine to provide a sharp crack. The specimen is finally broken in a tensile test, the failure load is recorded and the crack geometry is measured to give the data required to determine K_{Ic}.

The advantages of the CNT specimen
The advantages of the small specimen over existing compact tension testing specimens are its reduced size, ease and economy of manufacture, and ease of testing. In tests conducted, acceptable results have been achieved using a 9.5 mm diameter specimen whereas standard compact tension tests require dimensions varying in thickness from 20 mm up to 80 mm, depending upon the material.

The CNT specimen has a simple cylindrical shape making manufacture in a lathe a simple process. Also the small diameter means that the forces required to produce failure of the specimen are low, simplifying the testing apparatus required.

A further advantage of the much smaller physical size is that it can be used in many applications not possible with the standard CTT specimens. For example, the reduced size means that specimens can be taken from batch production material and from a failed component or structure in a post-mortem analysis to determine the cause of the failure, where the thickness of the components would not allow valid K_{Ic} testing using a CTT specimen.

Current commercial costs to determine K_{1c} for a material using 4 compact tension specimens are in the order of $5,000. This is a significant impediment to the application of fracture mechanics in industry. The CNT specimen being developed costs about one tenth of the standard specimen

An innovation in the present work is the procedure for growing the circumferential crack using a rotating beam fatigue machine. The methodology for sensing the associated growth of the crack, and further interpreting the results when the final uncracked ligament is eccentric is new. The depth and shape of the crack is not known until the specimen is finally broken in tensile testing to establish K_{Ic}.

Requirements for validity
It is required for valid K_{Ic} testing that only a minimal amount of plastic flow during fracture so that the conditions appropriate to linear elastic fracture exist. Normal compact tension CTT specimens with through-thickness cracks are generally required to be relatively large and bulky in order to satisfy the

high restraint and plane strain requirements for test validity. Due to the axisymmetric symmetry of the CNT specimen, plane strain conditions and low plasticity can be established despite the small size.

Our current work is aimed at determining the correct size of specimen and crack depth for higher toughness materials than originally tested.

Normal compact tension specimens are required to be large to achieve a condition where the free surface regions are negligible compared to the internal plane strain zone. However, in the cylindrical specimen the circumferential crack which is developed at the bottom of the notch has no end or free surface and therefore there is no end to the plane stress zone. In CNT specimens the required minimum depth of this crack is defined by the need to ensure that the crack tip zone is not influenced by the free surface shoulder of the notch from which the crack was grown.

The dimension of the ligament which remains for the final tension test in both the CTT and CNT specimen must be sufficient to ensure that yielding does not occur across the entire section in the cylindrical part of the specimen. Here the cylindrical specimen has a distinct advantage. The von Mises and Tresca criteria for plastic flow depend on the maximum shear stress in the material. For example, by the Von Mises criterion yielding initiates when

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_y^2 \qquad (1)$$

where σ_i are the principal stresses and σ_y is the uniaxial yield strength.

Hydrostatic tension is not relevant to yield according to the Von Mises criterion and this is very closely true for metals under most conditions. In the cylindrical specimen lateral contraction in the section of the notch is constrained by the surrounding material in the unstressed shoulder of the notch. As a result a high triaxial state of tension exists reducing the tendency for yielding to occur according to equation 1. The algebraic sum of the principal stresses at the notched section can rise to over 3 times σ_y before limits to elastic behaviour are encountered[5]. This constraint phenomenon greatly increases the ability of the small specimen test to maintain conditions appropriate to the application of linear elastic fracture mechanics at the crack tip.

Initially a finite element study was carried out to compare the finite element solution for the stress intensity factor at the crack tip with known analytical solutions and thus validate the model and the method for determining K_{Ic}. The finite element analysis was in all cases based on three-dimensional, isoparametric hexahedral and pentahedral elements. A specimen with a uniform fatigue crack depth was examined, giving a symmetric geometry and allowing the model to be reduced to a study of a two-degree wedge of the specimen. The specimen modelled was taken from an aluminium alloy Mirage wing spar on which considerable tests had been conducted by the Aeronautical Maritime Research Laboratories. The load used in the finite element analysis was that experimentally recorded at brittle fracture of the specimen. The crack depth is considered to be the combined depth of the notch and the fatigue crack.

Stresses in the axial direction, σ_{YY} , ahead of the crack tip are plotted in Figure 3. For simplicity a direct stress approach was implemented matching the stresses ahead of the crack tip to the analytical formula for plane strain

$$K_1 = \sigma_{YY}\sqrt{(2\pi r)} \qquad (2)$$

An elastic-plastic analysis was then conducted implementing both a linear hardening rule and then perfect plasticity. The results of the first analysis is shown in Figure 4 indicate the plastic zone approximates the plane strain zone size as expected for the cylindrical specimen but that the zone size increases as the crack becomes shallower. on the basis of this result it was decided that the depth for the fatigue crack had to be at least twice the Irwin plastic correction radius for the crack tip to not be influenced by the free surface shoulder of the machined notch.

The model was then loaded till net-section yielding occurred. It is seen that this required that the stress in the section of the crack had to be raised to almost three times the Uniaxial yield stress of the material confirming the large amount of constraint occurring in the notched specimen. On the basis of these results the diameter required for the notched specimen could be determined and is plotted in Figure 5. The size advantage over the standard test is clearly evident.

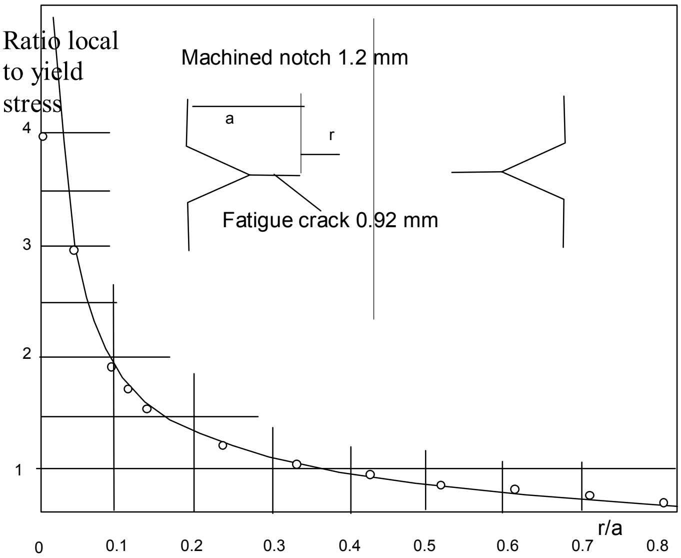

Figure 3 Ratio of local stress (σ_{yy}) to yield stress at a distance r ahead of the crack tip in a **CNT specimen.**

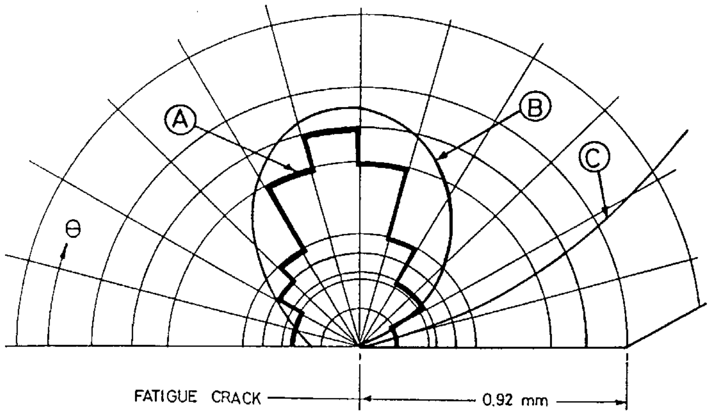

Figure 4 Results of an elastic-plastic analysis with linear hardening rule.

The results indicate that the plastic zone approximates the plane strain zone size for the cylindrical specimen. A is boundary of plastic zone, B. Von Mises approximation of plastic zone for plane strain conditions.

In all these analysis the elements at the crack tip were modified to model the crack tip strain singularity. The mid-side nodes were moved to the quarter side point as suggested in[6]. For the elastic case all elements meeting at the crack tip shared the same nodes giving the $1/\sqrt{r}$ strain singularity expected in linear elastic fracture mechanics. In the perfectly plastic case each element had different nodes allowing crack tip blunting and giving the 1/r strain singularity expected in this case[7].

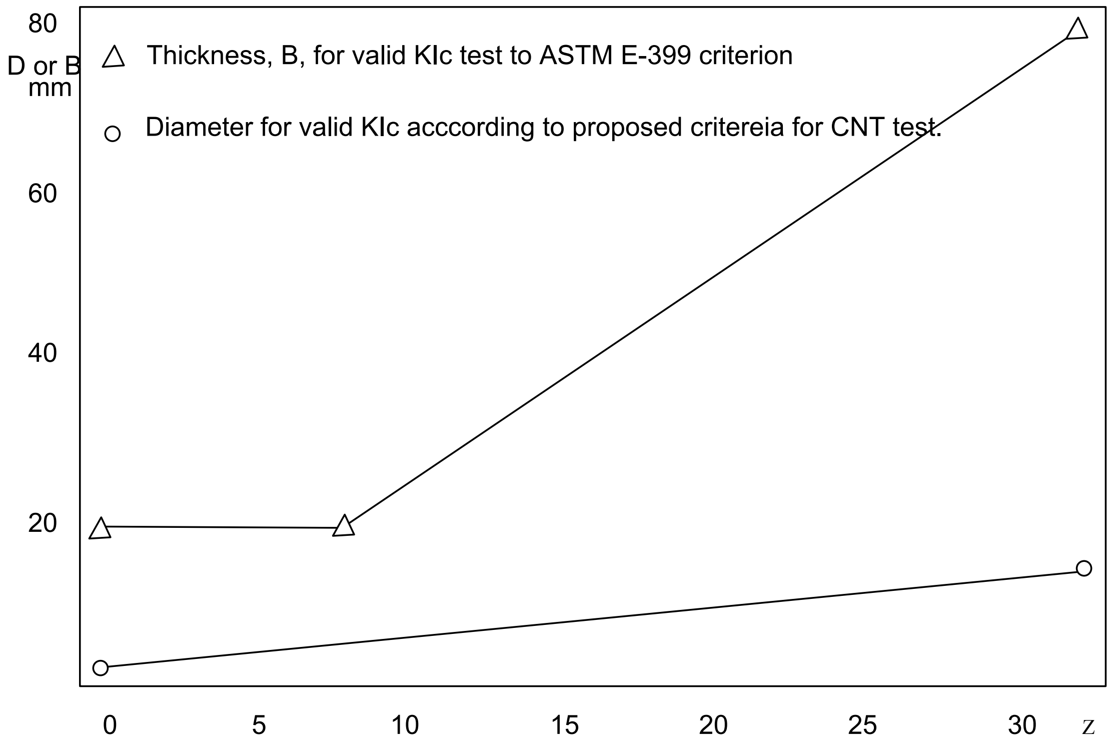

Figure 5 The diameter required for CNT specimens compared to CTT requirements ($Z = (K_{Ic}/\sigma_y)^2$

Experiemntal confirmation

Experimental studies have been conducted for which the results were compared with values obtained from compact tension specimens by the authors and at the Aeronautical and Maritime Research Laboratories in Melbourne[8]. In this work a large batch of 8.4 mm diameter specimens which collectively gave an experimental value for K_{Ic} of 31.6 MPa√m with a standard deviation of 0.98 MPa√m. These values compare with 31.6 with a standard deviation of 0.5 for tests by the AMRL using four 62.5X 60X 25 mm compact tension specimens. The results indicate that the new procedures will provide values of K_{Ic} of acceptable engineering accuracy (within 5%).

Information is currently available to justify the validity for K_{Ic} testing using the cylindrical notched test (CNT) specimen for only two different diameters (8 and 9.5 mm). The current dimensions are too small for valid K_{Ic} testing for high toughness, low yield strength materials with $(K_{Ic}/\sigma_y)^2$ greater than 18 mm. This restriction was satisfactory for the original development of the CNT specimen which was targeted at a hardened aluminium alloy but the restriction excludes materials used in many applications, for example, structural steels such as used in pressure vessels.

Recent tests at Monash have indicated a significant increase of applicability with CNT specimens if they are 15 mm in diameter. This is still small compared to the equivalent standard American Society for Testing Materials (ASTM) specimens which would be up to 200 mm thick. It is very difficult to find material of adequate thickness or testing machines capable of carrying out the ASTM tests. The effect of developing the CNT test to cover materials of higher values of $(K_{Ic}/\sigma_y)^2$ is to increase the usefulness of the test and extend the test to everyday use.

Correction factor to allow for eccentric fatigue cracks

The fatigue crack is grown in the notched specimen to provide a sharp crack for the tension test may not be exactly central to the notch. The crack is grown in a rotating fatigue machine under an applied moment but there is no guarantee that the crack growth will always be constant around the specimen, especially if the material properties are not uniform in the material from which the specimen has been machined. A procedure for correction for this eccentricity has been established[9,10].

CONCLUSIONS

The small cylindrical notched specimens which are pre-cracked by fatigue in a rotating bending machine which are described as cylindrical notched tesnile (CNT) specimens have been demonstrated to produce valid and reproducible K_{Ic} values over a wide range of toughnesses and materials. Validity limits and corrections for eccentricity of cracking have been developed.

The substantial advantages of the specimens smaller than the standard ASTM 399 type specimen allows testing in a wide range of conditions where K_{Ic} would otherwise be difficult to determine.

REFERENCES

1. R N Ibrahim, Y C Lam, and J W H Price, Effect of residual stresses and defects on the performance of aluminium pressure vessels, *Failure Analysis in Materials Engineering,* Materials Society of the IEAust, Melbourne March 1994.
2. H L Stark and R N Ibrahim, Crack Propagation in aluminium gas cylinder neck at constant load, *Engineering Fracture Mechanics,* Vol 48, pp 569-574, 1992.
3. H L Stark and R N Ibrahim, Estimating fracture toughness from small specimens, *Engineering Fracture Mechanics,* Vol 25, No 4, pp 395-401, 1986.
4. R N Ibrahim and H L Stark, Validity requirements for fracture toughness measurements from small circumferentially notched cylindrical specimens, *Engineering Fracture Mechanics,* Vol 28, No 4, pp 455-460, 1987.
5. J M Barsom and S T Rolfe, *Fracture and failure control in structures,* Prentice-Hall, NJ, 1988.
6. M H Alabadi and D P Rooke, *Numerical fracture mechanics*, Kluwer, Dordrecht, 1991.
7. R N Ibrahim and H L Stark, Crack propagation at room temperature in an extruded aluminium, *Engineering Fracture Mechanics,* Vol 30 , No 3, pp 409-414, 1988.
8. R N Ibrahim, The development of a small specimen for the evaluation of plane strain fracture toughness and the investigation of creep crack growth in aluminium pressure vessels. *PhD. Thesis in Mechanical Engineering,* University of NSW, 1989.
9. R N Ibrahim and H L Stark, Establishing KIc from eccentrically fatigue cracked small circumferentially grooved cylindrical specimens, *Int J of Fracture*, **44**, 1990, p179 -188.
10. Ibrahim, R N "CNT Small Specimen Testing Procedure to Evaluate Fracture Toughness" pp 735-743, ICPVT-9 Sydney, 9-14 April,2000